

Learning about the CP phase in the next 10 years

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Abstract

We assess the sensitivity to the lepton CP phase by accelerator and reactor experiments in the near future, characterizing it globally by means of the CP exclusion fraction measure. Such measure quantifies what fraction of the δ_{CP} space can be excluded at given input values of θ_{23} and δ_{CP} . For some region of the parameter space, we find that T2K and NO ν A combined can exclude about 30% – 40% of the δ_{CP} space at 3σ with a 5 years running in each neutrino and antineutrino modes. A determination of the mass hierarchy would be possible for a modest portion of the parameter space at 3σ .

Keywords: Neutrino Physics, CP violation

1. Introduction

After the discovery of θ_{13} [1, 2, 3, 4], the attention has been turned upon the last two unknowns in the three neutrino oscillation framework, the lepton CP violating phase δ_{CP} and the neutrino mass hierarchy. Gathering any information on these two unknowns is highly valuable. The determination of the mass hierarchy combined with the observability or not of neutrinoless double beta decay might reveal the Dirac or Majorana nature of neutrinos. In such scenarios, one might envisage that future sensitivities on the sum of neutrino masses from cosmological data could provide a powerful tool to test the standard cosmology framework. In this work, we focus on how much information on δ_{CP} can be obtained by current neutrino oscillation experiments, namely T2K and NO ν A, as how this correlates with the mass hierarchy measurement.

Certainly, future facilities such as Hyper-Kamiokande [5] and LBNE [6] are supposed to have remarkable sensitivities to both hierarchy and lepton CP violation [7]. Nevertheless, given the time scale of such experiments, any knowledge of these quantities is valuable. The main goal of this manuscript is to show under which circumstances T2K and NO ν A,

are able to exclude a significant fraction of the δ_{CP} values.

2. The appropriate CP measure for T2K and NO ν A

In this paper, to quantify the experimental sensitivity of T2K and NO ν A to δ_{CP} in a global way, we use the *CP exclusion fraction*, f_{CPX} , where f_{CPX} is defined as the fraction of δ_{CP} values which can be disfavored at a given confidence level for a given set of input parameters [8, 9].

One may be tempted to say that choosing a measure to assess the CP sensitivity is to a large extent arbitrary. Ultimately, such assertion is indeed true. Nonetheless, we argue that for experiments like T2K and NO ν A, f_{CPX} is more useful than other routinely used measures. The CP violation fraction, for instance, gives us the fraction of δ_{CP} values for which CP violation can be established (see, e.g., Refs. [5, 10]). Regardless the straightforward binary “yes or no” message to CP violation, this measure suffers from the “bias” of choosing special reference points ($\delta_{CP} = 0$ or π) to discuss the sensitivity to CP phase, losing valuable information: even if the experiments aforementioned cannot establish CP viola-

tion, they may still disfavor some region of the parameter space.

The expected error in δ_{CP} , on the other hand, suffers from a conceptual problem when dealing with T2K and NO ν A. The interpretation of the allowed region as an error bar fails if such region consists of disconnected pieces or if there are multiple fake solutions and non-Gaussianities in the χ^2 [9].

Probably the most straightforward way of showing the sensitivity to δ_{CP} is to plot the allowed region in, say, the $\delta_{\text{CP}} \times \sin^2 \theta_{23}$ plane for many different input parameters. The issue for the experiments we are interested in is that even the 1σ allowed regions are very large, sometimes disconnected, making it hard to build up a global perspective of the situation.

Hence, we advocate that the most appropriate way of evaluating globally the CP sensitivity of these experiments is to make use of the f_{CPX} . We will present our results in the plane $\delta_{\text{CP}} \times \sin^2 \theta_{23}$, as θ_{23} now is the least constrained angle, affecting considerably the experimental outcome. In this work, we use the standard parameterization of the neutrino mixing matrix [11].

3. Results

In Fig. 1, we present the δ_{CP} sensitivity for the combination of T2K and NO ν A, assuming a running of 5 years in each neutrino and antineutrino mode for both experiments. We take into account that θ_{13} is expected to be measured by Daya Bay with an error of ~ 0.005 . The details of the simulations can be found in Ref. [12], as well as a qualitative discussion based on the bi-probability plots and on spectral information.

Very roughly, the f_{CPX} contours for normal as input can be obtained by reparametrizing $\delta_{\text{CP}} \rightarrow \pi - \delta_{\text{CP}}$ in Fig. 1. We show on the top panel the result marginalizing over the hierarchy. We can see that generically, as $\sin^2 \theta_{23}$ grows, the sensitivities are worsened. When θ_{23} goes to the second octant, it boosts the leading (CP conserving) $\nu_\mu \rightarrow \nu_e$ oscillation term, inducing an increased number of ν_e appearance events. Although this improves the sensitivity to θ_{13} , such events are a *background* to the CP phase search, deteriorating f_{CPX} .

Another salient feature is the disparate performance for positive and negative values of δ_{CP} . What happens here can be understood by the degeneracy between δ_{CP} and the hierarchy [12]: in this region, the wrong hierarchy is likely to provide a very good fit of the data for values of δ_{CP} which would be disfavored in the correct hierarchy fit. This brings us to the bottom panel in Fig. 1, where we fit the expected data with only the normal hierarchy, that is, *the wrong hierarchy*.

T2K+NO ν A: 5 + 5 years each – inverted hierarchy
99.73% C.L.

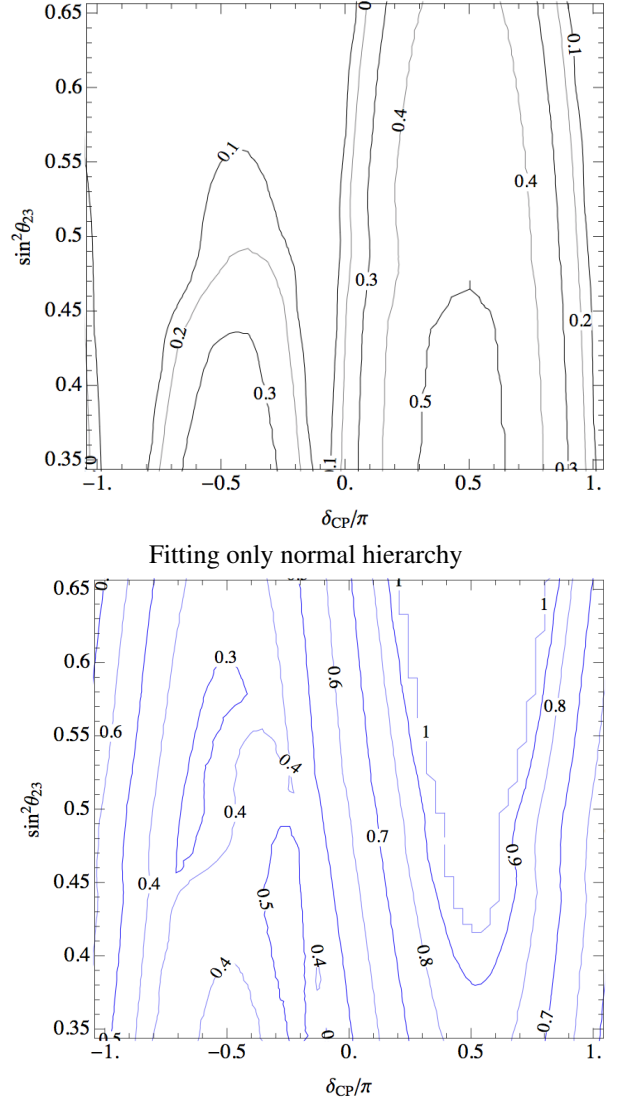


Figure 1: f_{CPX} isolines on the $\delta_{\text{CP}} - \sin^2 \theta_{23}$ plane at 3σ , for T2K and NO ν A running in $\nu + \bar{\nu}$ mode for 5 + 5' years, assuming inverted hierarchy as input. On the top, we marginalized over the hierarchy, while on the bottom we fit only the normal hierarchy (that is, the wrong hierarchy in this case).

On the left side of the plane, most of the wrong hierarchy δ_{CP} values can fit the data, displaying the degeneracy between δ_{CP} and the hierarchy. This reduces the f_{CPX} to the point that it becomes zero (at 3σ) for a large portion of the input parameters. On the other side of the parameter space, the degeneracy is lifted mainly due to the matter effects in NO ν A, while the final size of the allowed region of δ_{CP} is decisively impacted by the performance of T2K – an evidence for the synergy

between these experiments. For maximal values of δ_{CP} , there is the possibility of even rejecting the wrong hierarchy at 3σ . Although this sounds very promising, we call the attention that such a scenario is restricted to a fairly small fraction of the parameter space.

A few comments are in order regarding the θ_{23} octant determination. The octant degeneracy has its roots in the dependency of the disappearance mode $\nu_\mu \rightarrow \nu_\mu$ and its CPT conjugate in $\sin^2 2\theta_{23}$. By themselves, these modes cannot determine the octant of the atmospheric mixing angle. The appearance mode $\nu_\mu \rightarrow \nu_e$ and its CP conjugate, on the other hand, have an intricate dependency on δ_{CP} , $\sin^2 \theta_{23}$, and on the hierarchy, and they are plagued by degeneracies [13]. The inclusion of antineutrino running is essential to break these degeneracies, being an indispensable ingredient for both the CP phase the octant [12] sensitivities. The issue is the loss of statistics when running in the antineutrino mode due to smaller fluxes and cross sections. We have checked that the octant sensitivity does not change much if the antineutrino share is between 30% to 70% of the total running time. This, together with the importance of the determination of δ_{CP} and the hierarchy, indicates that the octant determination should play a minor role in the experiments run planning.

4. Conclusions

In the next 10 years, we do not expect a precise measurement of the lepton CP phase, as the present neutrino oscillation experiments have very limited statistics for such goal. Notwithstanding, given the large value of θ_{13} , these experiments may be able to provide valuable information on the phase. Depending on the true values of δ_{CP} and θ_{23} , they might be able to strongly disfavor a reasonable region of the parameter space.

We have quantified the expected sensitivity of T2K and NO ν A by using the CP exclusion fraction – the fraction of the CP values that can be excluded for a given input at a given confidence level (we adopted 3σ in this paper). We have shown that, for some region of the true parameter space, about 30% – 50% of the δ_{CP} space can be strongly disfavored with a 5 years running in each neutrino and antineutrino modes. This is because of the synergy between T2K and NO ν A, as the latter is more sensitive to the hierarchy, due to a longer baseline, while the first is more sensitive to the phase, once the wrong hierarchy is disfavored. In fact, there is even a modest possibility of determining the neutrino mass hierarchy at 3σ in the next 10 years.

The use of the antineutrino appearance channel is crucial for obtaining information on δ_{CP} , the optimal situ-

ation being the equal share between neutrino and antineutrino runnings.

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